

Magnetoresistive Random Access Memory with Reduced
Switching Field Variation

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FIELD OF THE INVENTION

This invention relates to semiconductor memory
devices and, more particularly, to the switching
characteristics of an array of multi-layer magnetic
10 memory cells.

BACKGROUND OF THE INVENTION

In the past, a variety of magnetic materials and
15 structures have been utilized to form magnetoresistive
materials for non-volatile memory elements, read/write
heads for disk drives, and other magnetic type
applications. Resistance changes due to relative changes
in the magnetic states of constituent magnetic regions
20 within these structures allow information to be stored,
in the case of memories, or read, in the case of read
heads. Memories made of magnetoresistive material, such
as Magnetic Random Access Memory (hereinafter referred to
as MRAM) has the potential to overcome some of the
25 shortcomings associated within memories currently in

production today. Dynamic Random Access Memory (DRAM),
Static Random Access Memory (SRAM), and Flash are the
three dominant types of memories currently in use. Each
of these memory devices uses an electronic charge to
store information and each has its own advantages and
disadvantages. SRAM has fast read and write speeds, but
it is volatile and requires large cell area. DRAM has
high density, but it is also volatile and requires a
refresh of the storage capacitor every few milliseconds.
This requirement increases the complexity of the control
electronics. FLASH is the major nonvolatile memory
device in use today. FLASH uses charge trapped in a
floating oxide layer to store information. Drawbacks to
FLASH include high voltage requirements and slow program
and erase times. Also, FLASH memory has a poor write
endurance of 10^4 - 10^6 cycles before memory failure. In
addition, to maintain reasonable data retention, the
thickness of the gate oxide has to stay above the
threshold that allows electron tunneling, thus
restricting FLASH's scaling trends. MRAM has the
potential to have the speed performance similar to DRAM
without the need for refresh, have improved density
performance over SRAM without the volatility, and have
improved endurance and write performance over FLASH.

As mentioned above magnetoresistive devices and MRAM in particular rely on resistance changes resulting from changes in the magnetization directions of constituent magnetic layers in the material stack. Typically, MRAM devices comprise a magnetic layer whose magnetization direction is fixed, the fixed layer, and a magnetic layer, the free layer, whose magnetization direction is free to switch between two or more stable directions separated by a spacer layer of an oxide (Tunneling magnetoresistance) or conductor (Giant magnetoresistance). Typical MRAM architectures involve laying out the individual magnetoresistive elements at the intersection of a crosspoint of mutually perpendicular current lines. These lines need not be in contact with the element. Their purpose is mainly to provide the magnetic fields, by having current passed along their length, to switch the magnetization direction of the free layer, within the element. In the absence of these fields, the magnetization direction of the free layer is stable. This is the procedure by which information is written to the memory. Reading information is typically accomplished by passing a small current through the element and comparing the resistance to a reference resistance.

For the successful operation of an MRAM device, it is required that the magnetic behavior of the free layers of an array of elements be very uniform. This is related to the crosspoint architecture mentioned above. The
5 current lines each provide enough current to produce approximately half of the magnetic field required for the free layer to alter its state, i.e. half the switching field. Magnetic state is defined here as a stable direction of the magnetization of the free layer. The
10 two half fields combine at the point of intersection of the current lines to provide enough field there so that the elements' free layer magnetic state will change. All other bits in the array are exposed to at most approximately half the switching field. The uniformity
15 in the magnetic behavior or the switching field for the array of bits is essential so that the half fields produced do not inadvertently cause an unwanted bit to switch its state and, in addition, that the two half fields combine to switch all the bits in the array.

20 It would be highly advantageous and is the intention of the current application, therefore, to provide means of decreasing the variation in the switching field bit to bit.

25 BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and further and more specific objects and advantages of the instant invention will become readily apparent to those skilled in the art from the following detailed description of a preferred embodiment thereof taken in conjunction with the following drawings:

FIG. 1 is an enlarged, simplified side view of a multi-layer magnetic memory cell, in accordance with the preferred embodiment of the present invention;

FIG. 2 attached is a graph of the relative variation of a magnetic intrinsic anisotropy verses a thickness of a single bulk nickel iron cobalt (NiFeCo) layer;

Fig. 3 illustrates the relative variation of the switching field of patterned bits verses a thickness of a single patterned nickel iron cobalt (NiFeCo) layer;

FIG. 4 is a simplified view of a magnetic memory cell used to experimentally measure a magnetic anisotropy and a relative magnetic anisotropy variation of a magnetic layer;

FIG. 5 is a graph of a relative magnetic anisotropy variation of the magnetic intrinsic anisotropy illustrated in FIG. 4 versus thickness of a magnetic layer; and

FIG. 6 is a graph of a relative switching variation of the magnetic memory cell illustrated in FIG. 1 for aspect ratios of two and three versus different combinations of material stack.

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Turn now to FIG. 1, which illustrates a simplified sectional view of a scalable magnetoresistive tunneling junction memory cell 10 in accordance with the present invention. The scalable magnetoresistive tunneling junction memory cell 10 includes a supporting substrate 12 onto which a seed layer 14 is positioned. Supporting substrate 12 may be, for example, a semiconductor substrate or wafer and semiconductor control devices may then be formed thereon. Seed layer 14 is formed on supporting substrate 12 to aid in the formation and operation of the remaining layers of material. An anti-ferromagnetic layer 16 is then positioned on seed layer 14 and includes, for example, alloys of manganese (Mn) and one of Ni, Fe, Pt, Rh or combinations thereof. It will be understood that seed layer 14 is optional and is included in this preferred embodiment for illustrative purposes. Also, the positioning of anti-ferromagnetic

layer 16 is for fabrication convenience with many other possible configurations available.

5 A first magnetic region 18 having a resultant magnetic moment vector 20 is positioned on the anti-ferromagnetic layer 16. A nonmagnetic separating layer 22 is placed on first magnetic region 18 and a second magnetic region 24 having a resultant magnetic moment vector 26 is positioned on nonmagnetic separating layer 22. Nonmagnetic separating layer 22 can be a dielectric material which behaves as a tunneling barrier to produce a magnetic tunnel junction that exhibits tunneling magnetoresistance or it may be a conductive material such as copper to produce a layered metallic structure which exhibits giant magnetoresistance. It will be understood that nonmagnetic separating layer 22 can include multiple insulating layers, but is shown as one layer for illustrative purposes.

20 Anti-ferromagnetic layer 16 pins resultant magnetic moment vector 20 unidirectionally along a preferred magnetic axis unless sufficient magnetic field is supplied to overcome the pinning action of layer 16. Generally, anti-ferromagnetic layer 16 is thick enough to insure that spurious signals and normal cell writing signals will not switch resultant magnetic moment vector 20.

In the preferred embodiment, fixed magnetic region 18 includes a synthetic anti-ferromagnetic layer material which includes a tri-layer structure of an anti-ferromagnetic coupling spacer layer 28 sandwiched between a ferromagnetic layer 30 and a ferromagnetic layer 32. However, it will be understood that magnetic region 18 can include a synthetic anti-ferromagnetic layer material other than a tri-layer structure and the use of a tri-layer structure in this embodiment is for illustrative purposes only. Further, magnetic region 18 is a fixed ferromagnetic region, meaning that the magnetic moment vectors of layers 30 and 32 are not free to rotate in the presence of a moderate applied magnetic field and layer 32 is used as the reference layer.

A free magnetic region 24 includes a synthetic anti-ferromagnetic layer material which includes N ferromagnetic layers that are anti-ferromagnetically coupled, wherein N is a integer number greater than or equal to two. In the embodiment shown here for simplicity, N is chosen to be equal to two so that magnetic region includes a tri-layer structure which has an anti-ferromagnetic coupling spacer layer 34 sandwiched between a ferromagnetic layer 36 and a ferromagnetic layer 38. Ferromagnetic layers 36 and 38 each have thicknesses 40 and 42, respectively. Further, anti-

ferromagnetic coupling spacer layer 34 has a thickness
44. It will be understood that the synthetic anti-
ferromagnetic layered material in magnetic region 24 can
include other structures with a different number of
5 ferromagnetic layers and the use of a tri-layer structure
in this embodiment is for illustrative purposes only. For
example, a five-layer stack of a ferromagnetic
layer/anti-ferromagnetic coupling spacer
layer/ferromagnetic layer/anti-ferromagnetic coupling
10 spacer layer/ferromagnetic layer could be used, wherein N
is equal to three.

Anti-ferromagnetic coupling spacer layers 28 and 34
most often include elements Ru, Os, Re, Cr, Rh, and Cu,
or combinations thereof. Further, ferromagnetic layers
15 30, 32, 36, and 38 most often include alloys of Ni, Fe,
Co, or combinations thereof. Ferromagnetic layers 36 and
38 each have a magnetic moment vector 46 and 48,
respectively, that are usually held anti-parallel by
coupling of anti-ferromagnetic coupling spacer layer 34.
20 Also, magnetic region 24 has a resultant magnetic moment
vector 26. When no magnetic field is applied, resultant
magnetic moment vectors 20 and 26 are oriented along a
preferred anisotropy easy-axis. Further, magnetic region
24 is a free ferromagnetic region, meaning that resultant

magnetic moment vector 26 is free to rotate in the presence of an applied magnetic field.

While anti-ferromagnetic coupling layers are illustrated between the ferromagnetic layers in magnetic regions 18 and 24, it will be understood that the ferromagnetic layers could be anti-ferromagnetically coupled through other means such as magnetostatic fields or other features. For example, for structures with a high aspect ratio, the ferromagnetic layers are anti-parallel coupled from magnetostatic flux closure. In this case, any nonmagnetic spacer layer that breaks the ferromagnetic exchange between layers will suffice. However, in the preferred embodiment, the adjacent ferromagnetic layers are anti-ferromagnetically coupled by sandwiching anti-ferromagnetic coupling material between each adjacent ferromagnetic layer. One advantage of using a synthetic anti-ferromagnetic layer material is that the anti-parallel coupling of the magnetic moment vectors prevents a vortex from forming at a given thickness where a vortex would be formed if using a single layer.

Further, during fabrication of scalable magnetoresistive tunneling junction memory cell 10, each succeeding layer (i.e. 14, 16, 30, etc.) is deposited or otherwise formed in sequence and each cell may be defined

by selective deposition, photolithography processing,
etching, etc. in any of the techniques known in the
semiconductor industry. During deposition of at least the
ferromagnetic layers 36 and 38, a magnetic field is
5 provided to set an easy magnetic axis for these layers
(induced anisotropy). This anisotropy axis can also be
set subsequent to deposition by annealing in the presence
of a magnetic field.

The structure of magnetic region 24 substantially
10 impacts the variation in the switching for an array of
MRAM devices. In the preferred embodiment, to minimize
the variation in the switching field H_{sw} , the magnetic
layer (i.e. layer 11) in magnetic region 24 adjacent to
nonmagnetic spacer region 22 is formed to have a
15 thickness greater than layer 38 and in the range of 40 Å
to 120 Å. A thicker layer 36 has been found to
significantly improve the magnetic properties of layer 36
so that H_{sw} is approximately equal from one MRAM device to
another. In general, it has been found that the
20 switching variation of the elements within the array is
impacted by the quality of the magnetic material
initially deposited on the nonmagnetic separating layer
22. Therefore, the essence of this patent is to optimize
the material quality of layer 36, and retain acceptable
25 switching characteristics by making layer 36 part of a

SAF structure. As mentioned above SAF structures provide a reduction in the formation of magnetization vortices (where the magnetization direction is not uniaxial but circular) and a way to control the switching field. See
5 United States Patent No. 6,531,723.

A significant degradation in the magnetic quality of magnetic layer 36 is seen starting at thicknesses below approximately 50 Å to 60 Å (See FIG. 2). This can be seen by an increase in the relative variation of the
10 intrinsic material anisotropy normalized to the mean anisotropy. Intrinsic material anisotropy is an energy defining the preferred stable uniaxial magnetization direction. The magnitude of the switching field H_{sw} for an unbalanced free magnetic region is controlled in part
15 by the intrinsic anisotropy (See United States Patent No. 6,531,723), and a larger variation in the intrinsic anisotropy will directly result from the increase in the variation of the magnetic switching field H_{sw} for patterned MRAM devices. Illustrated in FIG. 2 is the
20 relative variation of the intrinsic material anisotropy measured for various thicknesses 40 within a range approximately from 20 Å to 60 Å for magnetic layer 36 deposited in a magnetic field on an aluminum oxide layer
22 and annealed in a magnetic field at 250 °C for 30
25 minutes. As shown, the relative variation of the

intrinsic anisotropy decreases for thicker magnetic
layers which illustrates that magnetic memory cells grown
with thicker magnetic layers positioned adjacent to the
nonmagnetic spacer region will show improved magnetic
5 properties.

Turn now to FIG. 3 which illustrates a graph of the
relative variation of a magnetic switching field H_{sw} for
an array of patterned magnetic elements having a single
free magnetic layer (i.e. thickness 44 equals zero and
10 thickness 42 equals zero) verses thickness of the layer,
the layer being composed of nickel iron cobalt (NiFeCo)
grown on an aluminum oxide nonmagnetic spacer layer 22.
The size and shape of the elements are aspect ratio 2
ellipse shape with a width of 0.45 micrometers. As can
15 be seen in Fig. 3, there is a minimum in the relative
variation of the switching fields within the array
beginning at approximately 40\AA . Greater than 40\AA , the
relative variation is constant with thickness because it
is dominated by variations in shape anisotropy from bit-
20 to-bit that scale with the increasing moment. Below 40\AA
there is an increase in the relative variation with
decreasing thickness. This behavior is due to the
degradation in material quality shown in Figure 2. The
poor magnetic properties of the thin magnetic layer
25 directly increases the magnetic switching field variation

from one MRAM device to another in the array of MRAM devices. The preferred embodiment addresses these shortcomings by making layer 36 thicker with better material quality while effectively making the whole stack thinner by anti-ferromagnetically coupling layer 38 to 36. The preferred embodiment has the material quality of a thick layer but the shape contribution and lack of vortex formation of a thin layer.

Turn now to FIG. 4 which illustrates a magnetic memory cell 50 used to experimentally measure a magnetic anisotropy and a relative magnetic anisotropy variation of SAF layers 72. In a preferred embodiment, cell 50 includes a conductive layer 52. An insulator layer 54 is positioned on conductive layer 52 and a magnetic layer 56 with a thickness 58 is positioned on insulator layer 54. An anti-ferromagnetic spacer layer 60 with a thickness 62 is positioned on magnetic layer 56 and a magnetic layer 64 with a thickness 66 is positioned on spacer layer 60. Further, an insulator layer 68 is positioned on magnetic layer 64 and a conductive layer 70 is positioned on insulator layer 68.

In this specific example, conductive layers 52 and 70 include tantalum (Ta) and insulator layers 54 and 68 include aluminum oxide (AlO). Further, in this specific example, magnetic layers 56 and 64 include nickel iron

(NiFe) and spacer layer 60 includes ruthenium (Ru) wherein magnetic layers 56 and 64 are anti-ferromagnetically coupled. It will be understood that the materials included in layers 52, 54, 56, 60, 64, 68, and 70 of this specific example are chosen for simplicity and ease of discussion to illustrate a measurement result and that other materials could be chosen.

In the preferred embodiment, magnetic layers 56 and 64 are anti-ferromagnetically coupled by spacer layer 60. However, it will be understood that magnetic layers 56 and 64 can be magnetically coupled through other means. Further, cell 50 is illustrated as including two magnetic layers (i.e. layers 56 and 64) for simplicity and ease of discussion to show the experimental measurement.

Turn now to FIG. 5 which illustrates a graph of a relative magnetic anisotropy variation of the SAF structure 72 verses thickness 66 as illustrated in FIG. 4. In this illustration, thickness 66 is varied from approximately 20 Å to 120 Å wherein thickness 58 is approximately 40 Å. As shown, the relative magnetic anisotropy variation is approximately constant as a function of thickness 66. This result indicates that the variation depends substantially on thickness 58 (See FIG. 2) adjacent to tunneling barrier junction 54 and is

independent of subsequent layers magnetic grown thereon
(i.e. layer 64).

Turn now to FIG. 6 which illustrates the measured improvement of the switching distribution width (σ) of patterned bits by depositing the thick layers of an unbalanced SAF first on the tunnel barrier 22. Shown in FIG. 6 is a ratio of a variation for a thin magnetic layer 38 grown on a thick magnetic layer 36 divided by a variation of a thick magnetic layer 38 grown on a thin magnetic layer 36 as a function of the thin layer thickness for an array of aspect ratio 2 and 3 ellipse shaped bits of width 0.45 micrometers. For example, as thinner layer in 24 increases from 15 Å to 45 Å, the ratio of the sigmas from depositing the thick layer first on the tunnel barrier 22 to depositing the thin layer first on 22 increases from approximately 0.6 at 15 Å to 0.95 at 45 Å. The variation within an array can be reduced by as much as 40% by depositing the layer with good material quality on the tunnel barrier 22. This result indicates that for thicknesses below approximately 50 Å the variation in the switching field for an array of elements is reduced when the thicker layer is deposited on the tunnel barrier 22. Various changes and modifications to the embodiments herein chosen for purposes of illustration will readily occur to those

skilled in the art. For example, thickness is one method
for improving the material quality. In addition improved
material quality can be obtained from deposition of an
amorphous alloy, such as CoFeB alloys, on top of the
5 tunnel barrier. Also material quality can be improved
through high temperature anneals and depositions. To the
extent that such modifications and variations do not
depart from the spirit of the invention, they are
intended to be included within the scope thereof which is
10 assessed only by a fair interpretation of the following
claims.

Having fully described the invention in such clear
and concise terms as to enable those skilled in the art
to understand and practice the same, the invention
15 claimed is: